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HOLOGRAPHY:
a general survey

E.W. Taylor, M.A.(Cantab.), C.Eng., M.I.E.E

Research Department, Engineering Division
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HOLOGRAPHY: A GENERAL SURVEY

E.W. Taylor, M.A.(Cantab.), C.Eng., M.I.E.E.

Summary

The history of the development of holography is surveyed and an introduction to the general theory is given. Techniques for the preparation of holograms are described, and materials for use as holographic recording media are discussed. An extensive list of references is included.

Issued under the authority of

P. Rainger

Head of Research Department

Research Department, Engineering Division,
BRITISH BROADCASTING CORPORATION
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FOREWORD

This report is intended as an introduction to the subject of holography. It contains no original material, its purpose being to provide, in a convenient form, background material for two subsequent reports which deal with possible applications in the field of broadcasting.

HOLOGRAPHY: A GENERAL SURVEY

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HOLOGRAPHY: A GENERAL SURVEY
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1. Introduction and historical survey

In 1949 Gabor,[1,2,3,18] basing his ideas on principles suggested by Bragg,[4] put forward a 'two step' method of optical imagery. In the first step the object (essentially a transparency) was illuminated with coherent monochromatic light and the diffraction pattern resulting from interference between light scattered from features in the object and light passing directly through it was recorded on a photographic plate. In the second step the processed plate itself was illuminated with monochromatic light. The diffraction of light by the pattern recorded on the plate gave rise to two additional components of radiation, one of these components being a reconstruction of the original wave-front issuing from the object. This component gave rise to a 'reconstructed' image of the original object occupying the same position in space (relative to the plate) as the original object.* The other component was the so-called 'twin wave': this occurred because there were two object positions which could give rise to the same recorded diffraction pattern, and images in both these positions were reconstructed. The name of 'hologram' was given to the photograph of the original diffraction pattern, because (to quote from Reference 2) 'the photograph contains the total information required for reconstructing the object, which can be two-dimensional or three-dimensional'.

Gabor's work was directed towards improving the resolving power of electron microscopes by forming the hologram of a small object in electron radiation and reconstructing the image of the object in light radiation using an appropriately enlarged version of the hologram. Because of technical difficulties concerned with electrical and mechanical stability this aspect of the work was not successful. Difficulties were also experienced in reconstructing the image: in particular, the presence of the twin-wave meant that the wanted image always had to be viewed against an unwanted out-of-focus background. The difficulty of obtaining sufficiently monochromatic and coherent light sources also contributed to the initial lack of interest in the subject.

A fairly simple method of eliminating the twin-wave problem was demonstrated by Leith and Upatnieks[5] in 1962. This consisted of providing an off-axis 'reference wave', so that interference occurred between this wave and light passing through the object (which was still only considered as a transparency). The recorded diffraction pattern obtained with this arrangement had a regular 'grating-like' structure, and as with a conventional diffraction grating gave rise to two deviated components travelling in different directions when illuminated with monochromatic light. One of these components constituted the required reconstructed object wave-front and the other component constituted the unwanted twin wave: separation of the components was obtained simply by observing in the appropriate direction. Radiation from the same source must be used to illuminate the object and at the same time provide the reference wave. This is relatively easy to arrange in the case of light radiation, by using a beam-splitting system, but in the case of electron radiation no beam-splitting system is available and so off-axis holography is not possible. Gabor recognised this limitation when stating[2,18] 'it is very likely that in light optics, where beam splitters are available, methods can be found for providing the coherent background which will allow better separation of object planes and more effective elimination of the effects of the 'twin wave' than the simple arrangements which have been investigated'.

Leith and Upatnieks were also responsible[6] for introducing the idea of diffuse illumination holography. This step was largely made possible by the development of the laser[16,17] which made available, for the first time, a source of intense coherent light. Several advantages were found in illuminating a transparent object with diffuse light. As the light passed through the object in many directions, light from any one part of the object was spread over the entire area of the hologram: thus any portion of the hologram contained information concerning the entire object and a complete image could be reconstructed from it. Furthermore, surface imperfections on the hologram or other parts of the optical system (blemishes, dust particles, etc.) did not give rise to discrete effects in the reconstruction (as was the case with non-diffuse illumination), but only added to the overall flare or 'veiling glare' in the reconstructed image. (In fact, the effect of surface imperfections in conventional optical imaging systems is always greater when using non-diffuse illumination, and some degree of diffusion is used whenever possible.) Another advantage of the use of diffuse illumination was that the whole reconstructed image could be viewed from a variety of directions without optical aids, whereas with non-diffuse illumination only the reconstruction of the part of the object lying on the line between the source of illumination and the eye could be so observed. In fact, if a three-dimensional diffusely reflecting object was used instead of a transparency, the reconstructed (virtual) image was also three-dimensional and gave the appearance of observing the original object through a window formed by the hologram itself. The 'twin-wave' reconstruction gave rise to a real image which was also three-dimensional but which had 'reversed parallax' or 'pseudoscopic' properties.[6,7,8,18]

A further point discussed by Leith and Upatnieks concerned the range of light intensities observable in the reconstructed image, as compared with the corresponding range obtainable in conventional photographic processes. In such a conventional process, energy from small, very bright areas of the object is concentrated in localised regions of the photographic plate, where 'over-exposure' of the emulsion may then occur: these areas are therefore reproduced at less than their true relative intensity in the developed photographic image. In diffuse holography, on the other hand, the energy from such object areas is spread over the whole area of the photographic plate, thus preventing local over-exposure, and these areas are reproduced at their correct relative intensity in the reconstructed image. Leith and Upatnieks reported intensity ranges of up to 10^5 between the brightest regions and the smallest distinguishable intensity steps in reconstructed images: this represented a considerable increase in intensity range, compared with conventional photography.

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* Provided that radiation of the same wavelength and the same geometry was used in both halves of the two-step process.

A disadvantage in the use of diffuse coherent illumination is the appearance of the so-called 'speckle pattern', a fine random granular pattern produced by mutual interference between components of reflected light enamating from the different elementary portions of the surface. This effect is discussed in Section 3.

Two further inter-related developments in holography may be briefly mentioned. Leith and Upatnieks[6] proposed a system by which a coloured holographic image could be reconstructed, in which the original object was illuminated with coherent light in each of the three primary colours, and three (superimposed) holograms* were formed, each corresponding to one such colour. Image reconstruction was also carried out using light of each primary colour, the three 'colour-separation' images appearing superimposed to form a final coloured image. Each colour-separation hologram, however, would give rise to an image in light of each wavelength, so that a total of nine reconstructions of the image would appear. Various suggestions have been made[6,9,10,11,12,13,18] as to how to separate the six unwanted 'crosstalk' images from the three wanted ones; of these suggestions the one made by Lin, Pennington, Shobe and Labeyrie[11,12] is particularly interesting as the resulting hologram may be viewed in white light. The system used is in fact an extension of a holographic technique proposed by Denisyuk[14,15] in which light from the object and light in the reference wave fall on the photographic plate from opposite directions. The two interfering wave-trains therefore travel in opposite directions and the diffraction pattern consists of a series of surfaces approximately parallel to the plane of the photographic plate. Using a photographic emulsion whose thickness is relatively large compared with the wavelength of light, and arranging (by a bleaching process) that the record of the diffraction pattern is in terms of a variation in the refractive index of the emulsion rather than a variation of optical density, it can be seen that the hologram will be in the form of alternate nearly-parallel layers of high and low refractive index, similar layers being separated by one half wavelength of the light used. The hologram will therefore behave as an interference filter, and when illuminated by white light from the appropriate direction will only reflect light of the wavelength used when making the hologram, thus forming a reconstructed image of the object in the colour of the light used. If three colour-separation holograms are simultaneously produced in this way (by using, as before, three coherent sources of light, one of each primary colour), then the reconstructed colour-separation images will be superimposed on illumination with white light to give a final coloured image, without the appearance of the unwanted 'crosstalk' images.

The work briefly described above has provided the foundation for the very extensive developments in holographic technique which have since occurred. Laser radiation is now almost exclusively used for producing holograms because of its relatively long 'coherence length'. By 'coherence length' is meant the greatest distance between two points along the direction of propagation of the radiation such that significant correlation exists between the phase of the radiation at each point. This distance is equal to the greatest difference in path length in the two arms of an interferometer for which, when using the radiation under consideration, distinct interference fringes are produced: it is related to the degree of monochromaticity of the radiation.[18,19] In a gas laser the coherence length may be of the order of one metre: this may be contrasted with the coherence length of the radiation used by Gabor in his early work[1,2,3] which was of the order of a fraction of a millimetre. The use of radiation of large coherence length becomes essential in diffuse illumination holography, particularly when three-dimensional objects are involved.

2. Theory

2.1. An illustrative example

Following the treatment given to the subject by Smith,[18] the theory of holography is introduced by a simple example which serves to illustrate the main features of the subject. Consider two collimated beams (A and B) of monochromatic and mutually coherent light travelling horizontally (and therefore containing vertical plane wavefronts) and falling on the same area of a vertical flat photographic plate (P in Fig. 1). For simplicity, one beam is assumed to be normally incident onto the plate while the angle of incidence of the other beam in a horizontal plane

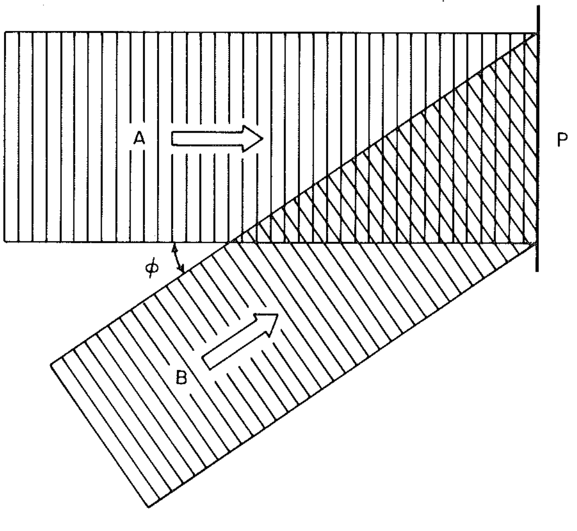

Fig. 1 - Two interfering beams

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* By analogy with colour photography and colour television nomenclature, these can be termed 'colour-separation' holograms.

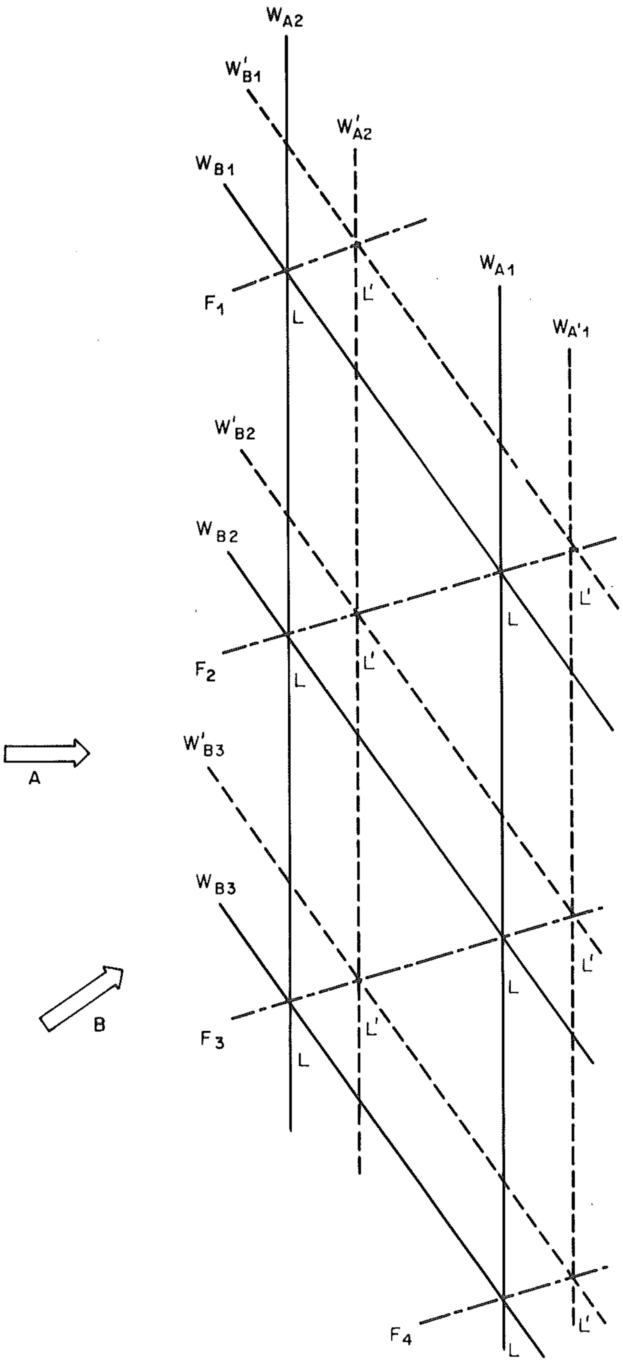

Fig. 2 - Two sets of interfering wavefronts

is ϕ. An interference pattern will be formed in the volume common to both light beams, and the light-sensitive emulsion of the photographic plate will intercept a cross-section of this pattern. The fringes in this cross-section will consist of a pattern of vertical equally-spaced straight lines. Fig. 2 shows a horizontal cross-section of an enlargement of a region close to the photographic plate. If the wavelength of the radiation* is λ, identical features in the electromagnetic field will occur in planes separated by this distance. W_{A1} and W_{A2} show the position of two such planes, at a certain instant of time, in the beam A of Fig. 1, while W_{B1}, W_{B2} etc. show corresponding features in the beam B. At the lines of intersection (L) of these two sets of planes the fields will reinforce each other to the greatest extent, and the maximum electromagnetic disturbance will occur. A short time later these features in the electromagnetic field will have moved to the planes W'_{A1}, etc. and W'_{B1} etc. which intersect at the lines L'. The parallel planes F_1, F_2 etc. containing the lines L, L', etc. as the waves progress will correspond with the regions of greatest electromagnetic disturbance in the interference pattern: in optical terms, these regions will show as bright areas. These planes are stationary in space and the interference pattern is therefore stationary. It can be seen from Fig. 2 that if the two wave trains in the beams A and B are not of the same wavelength, then the plans L, L' etc. are not stationary in space and the interference pattern therefore moves.

Returning to the case in which the wave-trains in the beams A and B are of the same wavelength, consider the exposure of the photographic plate (P in Fig. 3) which is placed normal to the beam A, and therefore parallel to the wavefronts W_{A1}, W_{A2} etc. As the interference pattern is stationary, a time exposure of the plate may be made. Considering the right-angled triangle XYZ, it can be seen that

$$XZ = \frac{\lambda}{\sin\phi}$$

hence, because the planes F_1 and F_2 are parallel

$$X'Z' = l = \frac{\lambda}{\sin\phi} \qquad (1)$$

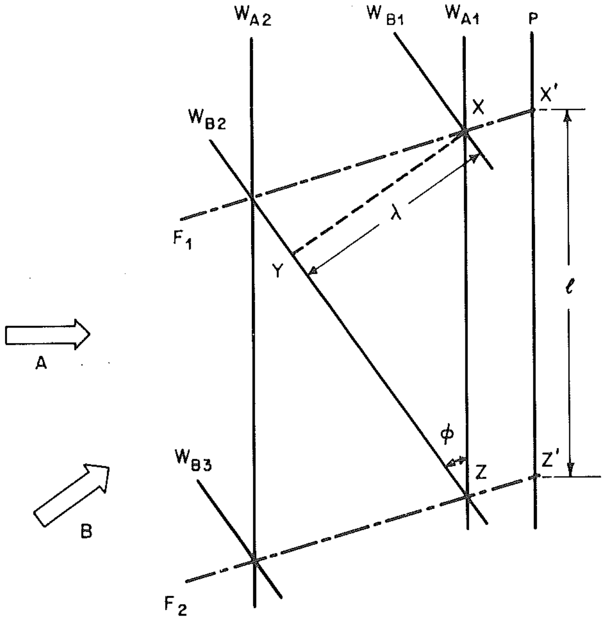

Fig. 3 - Geometry of 2-dimensional record of interference pattern

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* Note that this wavelength refers to radiation within the emulsion of the photographic plate, and is equal to λ_0/μ, where λ_0 is the free-space wavelength and μ is the refractive index of the emulsion. The angular relationships between the interfering beams of radiation also refer to conditions existing within the emulsion.

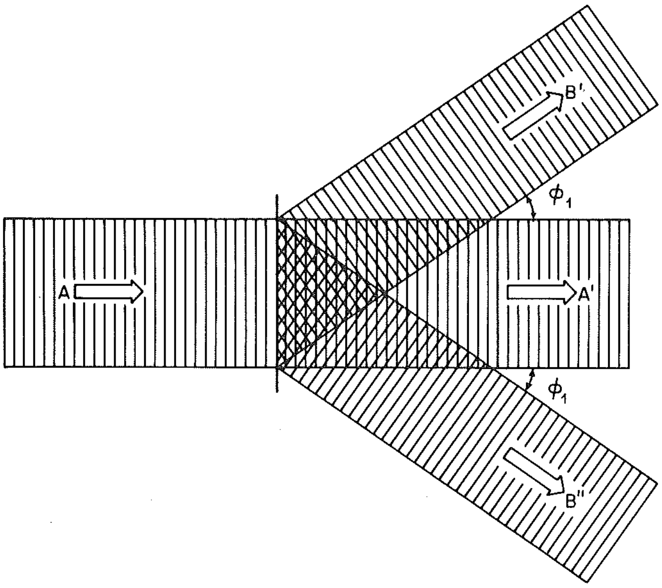

Fig. 4 - Diffraction from 2-dimensional recording

The distance l is the spacing of the fringes on the photographic plate. When processed, the plate will carry a series of alternately clear and opaque parallel stripes having the same spacing l, and will therefore behave as a diffraction grating. If illuminated by the beam A in Fig. 1, a number of beams will emerge from the plate travelling at angles ϕ_n to the normal to the plate, where[28]

$$\sin \phi_n = \pm n\lambda/l \qquad (n = 0, 1, 2 \ldots\ldots)$$

Since $\phi_0 = 0$, the condition $n = 0$ corresponds to the 'zero order' or undeviated beam (A′ in Fig. 4). The 'first order' ($n = 1$) diffracted beams (B′ and B″ in Fig. 4) emerge at angles $\pm\phi_1$, where

$$\sin \phi_1 = \lambda/l \tag{2}$$

Comparing Equations 1 and 2 it can be seen that $\phi_1 = \phi$, and that the beam B′ is therefore travelling in the same direction as the original beam B in Fig. 1. The beam B′ may therefore be regarded as a 'reconstruction' of the beam B. The beam B″ corresponds to the unwanted 'twin wave' (see Section 1). It may be regarded as the reconstruction of a hypothetical beam incident onto the plate at the same angle as the beam B in Fig. 1, but on the opposite side of beam A, as this hypothetical case would give rise to the same interference pattern, and therefore the same stripe pattern on the processed plate, as in the case discussed above.

If several 'object' beams are simultaneously incident at various angles onto the plate, in addition to the 'reference' beam A, interference patterns will be formed between each such beam and the reference beam. On illuminating the processed plate, reconstructions of each such beam will be produced, together with the respective 'twin waves'. Interference will also occur between each pair of object beams and these patterns, if recorded on the plate, would give rise to further spurious reconstructed beams. Such patterns are reduced in intensity by making the reference beam much stronger than the object beams (see Section 4.1.2). It is not essential for the reference beam to be normal to the plate, provided that the beam used for reconstruction is incident at the same angle.

2.2. Introduction to the general theory

In introducing the general theory of holography it is convenient to use the notation of complex quantities in describing electromagnetic field functions. Fig. 5 shows an Argand diagram in which a vector of length A makes an angle θ with the real axis. The angle θ is the 'phase angle' of the function relative to an arbitrary but constant reference (for example, relative to the instantaneous value of the function at a particular point in space). From Fig. 5

$$\mathbf{A} = A(\cos\theta + j\sin\theta)$$

or (by applying de Moivre's Theorem)

$$\mathbf{A} = Ae^{j\theta} \tag{3}$$

where letters in bold print denote vector quantities. The following relationship arising from the properties of complex variables[29,30] then hold:—

$$|\mathbf{A}| = A \tag{4}$$

$$|\mathbf{A}|^2 = \mathbf{A}\,.\,\mathbf{A}^* = A^2 \tag{5}$$

$$|\mathbf{A}+\mathbf{B}|^2 = |\mathbf{A}|^2 + |\mathbf{B}|^2 + \mathbf{A}.\mathbf{B}^* + \mathbf{A}^*.\mathbf{B} \tag{6}$$

where $\mathbf{A}^*$ is the complex conjugate of $\mathbf{A}$, so that

$$\mathbf{A}^* = A(\cos\theta - j\sin\theta) = A\,e^{-j\theta} \tag{7}$$

Also

$$\mathbf{A}^2 = A^2e^{2j\theta} \tag{8}$$

Light-sensitive materials are not affected by the phase of the incident radiation but respond only to the energy content of the radiation. This energy content is propor-

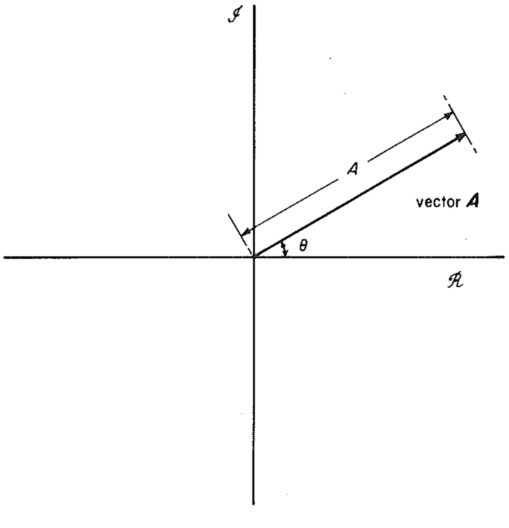

Fig. 5 - Argand diagram

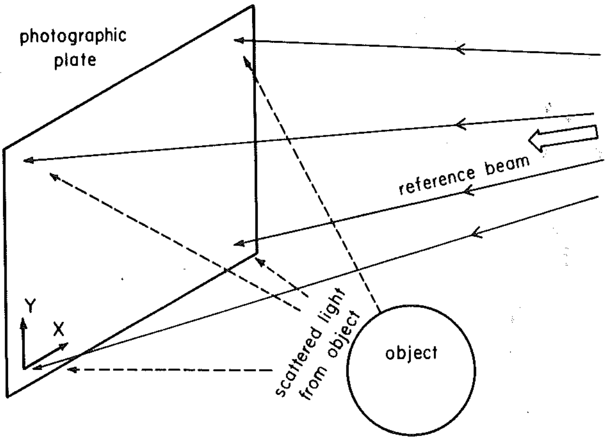

Fig. 6 - Illustration of holographic recording system (Object illuminating beam not shown)

tional to the square of the amplitude of the wave-motion. In this respect the term 'intensity' will be used to describe this quantity:* thus the intensity of the radiation (I_A) is given (from Equation 5) by

$$I_A = A^2 = |\mathbf{A}|^2 \tag{9}$$

Consider an 'object wave' (that is, a wave reflected from the object whose holographic image is required) and a 'reference wave', falling simultaneously on a photographic plate situated in a plane defined by the axes X, Y (Fig. 6). The two wave-motions are of the same wavelength and polarisation and are coherent, so that interference will occur in the volume common to both waves. A cross-section of the interference pattern will be recorded on the plate. Let $\mathbf{O}$ be the object wave and $\mathbf{R}$ be the reference wave at a particular point (x, y) on the plate. The amplitude and relative phase of the wave $\mathbf{O}$ are functions of the co-ordinates (x, y), this dependance conveying information about the object from which $\mathbf{O}$ emanates.** For simplicity it is assumed that the reference wave $\mathbf{R}$ is uniform over the plate so that (from Equation 9)

$$I_R = |\mathbf{R}|^2 = \text{constant} \tag{10}$$

The total field at (x,y) is $(\mathbf{O} + \mathbf{R})$ and the overall intensity (I_0) at this point is therefore given by

$$I_0 = |\mathbf{O} + \mathbf{R}|^2 \tag{11}$$

After suitable exposure the photographic plate is processed, and is then termed the 'hologram' (see Section 1). For the present discussion it will be assumed that this processing has resulted in a transfer characteristic such that*

$$T = a.I_0^2 \tag{12}$$

where T is the ratio of the intensities of light before and after passing through the hologram at the point (x, y)
and a is a constant

Since intensity is proportional to the square of the amplitude of the wave-motion (Equation 9) the amplitude transmittance (t) of the hologram (that is, the fraction by which the amplitude of a wave incident onto the hologram at the point (x, y) is reduced on passing through the hologram) is given by

$$t^2 = T$$

or

$$t = \pm T^{1/2} \tag{13}$$

The negative sign in Equation 13 has no physical significance, and therefore, from Equation 12,

$$t = b.I_0 \tag{14}$$

where b is a constant.

On illuminating the hologram with the reference beam $\mathbf{R}$ by itself, the field ($\mathbf{S}$) at the point (x, y) after the radiation has passed through the hologram is given by

$$\mathbf{S} = \mathbf{R}.t$$

$$= \mathbf{R}.b|\mathbf{O} + \mathbf{R}|^2 \tag{15}$$

from Equations 11 and 14. Expanding Equation 15 (using Equation 6)

$$\mathbf{S} = b[\mathbf{R}(|\mathbf{O}|^2 + |\mathbf{R}|^2) + \mathbf{R}.\mathbf{R}^*.\mathbf{O} + \mathbf{R}^2.\mathbf{O}^*] \tag{16}$$

$$= b[\mathbf{R}(I_0 + I_R) + I_R\,.\,\mathbf{O} + I_R\,.\,\mathbf{O}^*] \tag{17}$$

The first and second terms in Equation 17 are derived from the corresponding terms in Equation 16 using the relationships given in Equations 5 and 9; the third term is similarly derived using Equations 8 and 9, noting that as the eye (or any other photosensitive device) is insensitive to phase, the $e^{2j\theta}$ term in Equation 8 may be ignored. The first term in Equation 17 is a function of the illuminating radiation $\mathbf{R}$, modified in amplitude by a factor $b(I_0 + I_R)$: it therefore represents the 'zero order' component of the diffracted radiation, travelling in the same direction as the illuminating radiation. The second and third terms in Equation 17 represent the 'first order' components of the diffracted radiation. The second term is a function of the original object wave $\mathbf{O}$: because both b and I_R are constant (that is, independent of the co-ordinates (x, y) of the point on the hologram under consideration), this term represents an exact 'reconstruction' of the original object wave, which will give rise to an image identical in all respects to the original object. This image will be virtual, as it is formed in the position (relative to the hologram) occupied by the original object: that is, on the side of the hologram remote from the observer. The third term in Equation 17 is, similarly, a function of the wave O^*, which is identical with the object wave O except that all phase differences are reversed in sign (see Equation 7). This term represents the 'twin wave' and gives rise to a real 'conjugate' image on the observer's side of the hologram (see Section 1).

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* Many workers describe this quantity as 'intensity': however, Smith[18] refers to it as 'irradiance' and Ditchburn[28] refers to it as 'relative energy', reserving the term 'intensity' for photometry.

** This dependance also includes the 'speckle pattern' component, characteristic of diffuse illumination by coherent light (see Section 3).

* In photographic terms this is equivalent to saying that the plate has been processed to a 'gamma' of 2·0. The effect of this transfer characteristic is discussed in detail by Smith.[18a]

An alternative theoretical treatment, first proposed by Leith and Upatnieks[5] and described by Smith,[18] regards the interference pattern recorded on the hologram as being composed of a number of spatial Fourier components. Each such a spatial Fourier component acts as a diffraction grating and diffracts radiation into two first-order components. The superposition of the components of radiation from all the spatial Fourier components gives the total radiation field diffracted by the hologram and it can be shown that this field consists of a reconstruction of the original object wave, together with a conjugate twin wave, as previously described. A plane wave arriving at the photographic plate along the direction of propagation of the reference wave, and another arriving along a direction related to the overall position of the object, would give rise to a spatial Fourier component having a certain periodicity and orientation. This Fourier component may be regarded as a spatial 'carrier', all the other Fourier components of the recorded diffraction pattern being regarded as 'sidebands' carrying information about the characteristics of the object and the reference beam. It can be seen that as the angle between the reference beam and object directions is increased, the spatial frequency of the carrier is also increased, but at the same time the angle of diffraction of the reconstructed radiation is also increased. In a practical holographic system a compromise must always be made between these two factors: a large angle of diffraction assists in the separation of the wanted and unwanted diffracted components* but can only be achieved using a recording medium with adequate resolution. Fig. 7 shows a microphotograph of a portion of a hologram. It can be seen that individual elements of the recorded interference pattern have a general similarity in size and orientation, giving the hologram a pronounced uniformity of texture: this corresponds to the presence of the spatial carrier. On the other hand, individual elements of the recorded pattern differ greatly in their opacity, as well as to some extent in their size and orientation. These differences correspond to the spatial sidebands and carry the object information.

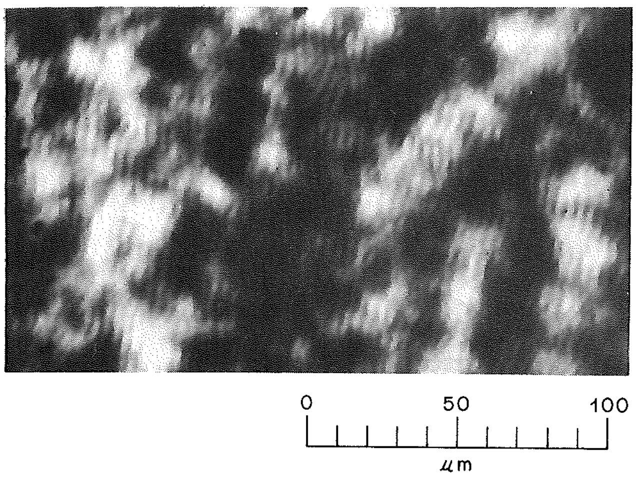

Fig. 7 - Microphotograph of a hologram

The fine structure is the recorded interference pattern: the relatively coarse structure is the recorded speckle pattern (see Section 3)

So far the description of the holographic process has assumed a process of diffraction caused by quasi-periodic modifications to the amplitude of the incident radiation. Diffraction will also occur if the phase of the incident radiation is modified[18b] by the hologram. Such phase changes will occur if the hologram consists of transparent material of uniform thickness in which the refractive index at a certain point is related to the intensity of radiation in the interference pattern at that point during formation of the hologram. Alternatively, the refractive index of the material may remain constant and the phase changes produced by variations in thickness of the material. Phase changes may also be produced by embossing or etching the diffraction pattern onto a reflecting surface. There is a twofold advantage in the use of such 'phase holograms' instead of the 'amplitude holograms' previously described. In the first place, the 'diffraction efficiency' (i.e. the proportion of the radiant energy incident onto the hologram during image reconstruction that is utilised in the wanted image-forming diffracted component) can be greatly increased.[18,28,31,32,33,34,92] In addition, many substances can be used to control the relative phase of the incident radiation while comparatively few provide the necessary control of its amplitude, thus extending the range of materials available for use in holographic recording. A summary of currently-available materials is given in Section 4.3.

2.3. The volume hologram

In Sections 2.1 and 2.2 it has been assumed that the recorded representation of the interference pattern which constitutes the hologram is two-dimensional: that is, it exists entirely upon the plane defined by the axes X, Y (Fig. 6).* A class of holograms exists, however, in which a volume of the interference pattern is recorded rather than a strict two-dimensional cross-section. A photographic emulsion, for example, always has significant thickness compared with the wavelength of light and the resulting 'volume' hologram[18,19,93,94] will consist of surfaces of differing optical density (or differing refractive index if a phase hologram is produced by bleaching as described in

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* Note in Equation 17 that the zero-order component is also 'modulated' (by virtue of the multiplying factor $b(I_0 + I_R)$, indicating that some light is diffracted away from the straight-through direction: the wanted diffracted component must be distinguishable from this unwanted component. (See Section 3).

* This is termed a 'surface' hologram.

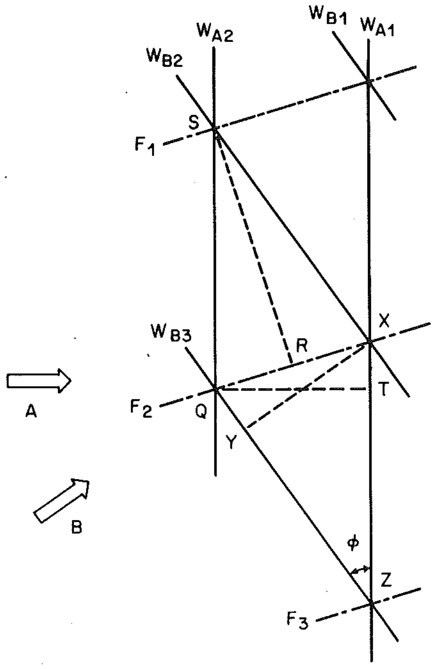

Fig. 8 - Geometry of 3-dimensional record of interference pattern

Section 3) spaced throughout the thickness of the emulsion. Diffraction from such a hologram may be illustrated by considering the case discussed in Section 2.1 where two beams of coherent light fall simultaneously onto the plate. In this case, however, the emulsion occupies the entire space shown in Fig. 3 instead of being confined to the plane P. This diagram is re-drawn in Fig. 8 with additional annotation. The following relationships* then apply:—

(i) QT is perpendicular to SQ and defines the direction of beam A (Fig. 1)

(ii) XY is perpendicular to QZ and defines the direction of beam B (Fig. 1). Furthermore, XY = λ, where λ is the wavelength of the radiation.

(iii) SR is perpendicular to QX and is of length d (the interference fringe spacing)

(iv) $X\hat{Z}Q = \phi$ (the angle between the directions of arrival of the two beams A and B).

(v) The quadrilateral QSXZ is a rhombus; hence $S\hat{X}Q = Q\hat{X}Z = S\hat{Q}X = \alpha$.

(vi) $X\hat{Q}T = Q\hat{X}Y = \beta$, where β is the angle between the interference fringes and the direction of arrival of either beam A or beam B.

It can be seen that

$$\alpha = 90^\circ - \phi/2 \qquad (18)$$

and

$$\beta = 90^\circ - \alpha \qquad (19)$$

Also, since (see Equation 1)

$$XZ = \frac{\lambda}{\sin\phi}$$

the fringe spacing (d) is given by

$$d = \frac{\lambda}{\sin\phi} . \sin\alpha$$

$$= \frac{\lambda}{2\sin\phi/2} \qquad (20)$$

from Equation 18. When processed, the diffracting surfaces in the hologram will consist of a number of parallel planes of spacing d as given in Equation 20.

In considering the behaviour of the hologram during the image reconstruction process, use is made of a relationship derived (in relation to X-ray diffraction from crystal lattices) by Bragg.[35] In Fig. 9 a set of parallel plane diffracting planes of spacing d are shown illuminated by a parallel beam of radiation of wavelength λ having a direction ψ relative to the diffracting planes. Bragg's Law states that the diffracted beam will emerge from the set of planes in such a direction as if specularly reflected by the planes (that is, so that the diffracted beam makes an angle 2ψ with the original beam). Furthermore, diffraction will only occur if the radiation components reflected from each plane are in phase: this leads to the relationship

$$2d\sin\psi = n\lambda$$

where n is an integer.

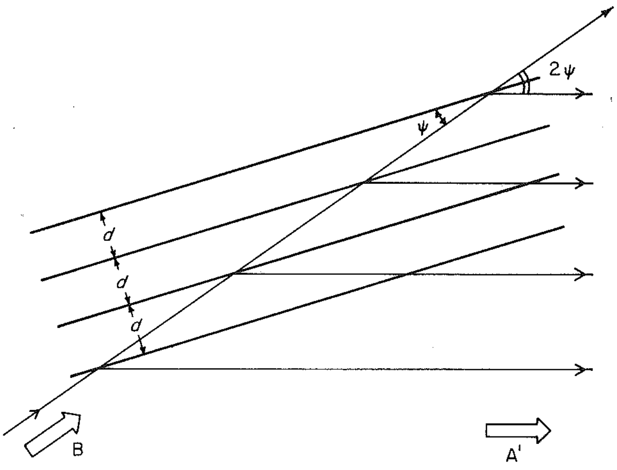

Fig. 9 - Diffraction from 3-dimensional recording

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* These relationships, and also the wavelength λ in Equations 20 – 22, refer to conditions within the emulsion of the photographic plate (see footnote on p.3).

In the present case (for first-order diffraction) $n = 1$, and

$$2d \sin \psi = \lambda \qquad (21)$$

Substituting for d from Equation 20,

$$2 \sin \psi \,.\, \frac{\lambda}{2 \sin \phi/2} = \lambda$$

hence

$$\psi = \phi/2 \qquad (22)$$

or from Equations 18 and 19

$$\psi = \beta \qquad (23)$$

The diffracting planes shown in Fig. 9 occupy precisely the same positions within the emulsion of the photographic plate as the interference fringes from which they were derived during the formation of the hologram. Equation 23 thus implies that the angle of incidence of the reconstructing beam onto the hologram must be the same as that of one of the original beams when forming the hologram. (Fig. 9 shows the case where the original beam B is used as the reconstructing beam (compare with Fig. 8), but the angular relationships are the same if reconstruction is carried out with beam A). Furthermore, the angle between the reconstructing beam and the resulting diffracted beam if $2\psi = \phi$ (from Equation 22): thus in the case shown in Fig. 9 the original beam A is reconstructed. The 'twin wave' beam will, however, not be reconstructed (although it can be obtained, by itself, by a different choice of reconstructing beam angle). This represents a considerable advantage, as in principle all the light incident onto the hologram may be diverted into the reconstruted beam.[32,33]

If, as discussed in Section 2.1, several 'object' beams are incident at various angles onto the plate, in addition to the reference beam A, separate sets of diffracting planes will be formed for each such object beam, and these beams will all appear during the reconstruction process, provided that the reconstruction beam approaches the hologram from the appropriate direction. As reconstruction will not take place if a volume hologram is illuminated other than at the correct angle, it is possible to superimpose volume holograms on the same plate, using different reference beam angles, and recover only the wanted image by suitable choice of reconstruction-beam angle. The change in reference-beam angle required to extinguish a reconstructed image depends on the number of diffracting planes present in the hologram: a detailed tratement of the subject is given by Smith.[18] The technique proposed by Denisyuk[14,15] for forming holograms which can be viewed in white light gives rise to volume holograms in which the diffracting planes are nearly parallel to the surface of the plate, and thus behave in a similar manner to dielectric interference filters.[28]

3. The speckle pattern

When an extended diffusely-reflected surface is viewed while illuminated by coherent light, the surface appears to be covered by a fine random granular pattern. This 'speckle pattern' is produced by mutual interference between components of reflected light emanating from the different elementary portions of the surface. The resulting interference pattern occupies the entire volume which is illuminated by light reflected from the object, and the cross-section of this interference pattern made by the photosensitive surface (e.g. the retina under conditions of visual observation) gives rise to the granular pattern.

When making a hologram of an object, the granular structure of the speckle pattern will be recorded on the holographic medium in addition to the wanted holographic interference pattern (see Section 2.2). On reconstructing the holographic image, some of the reconstructing light beam is scattered away from the straight-through direction because of the presence of this recorded random pattern, to form a 'flare' component. The angular extent of this flare component depends on the 'scale' (or average distance between similar features) of the recorded pattern; this in turn depends on the angle subtended by the object at the hologram, the speckle pattern becoming coarser as the size of the object is reduced. That this should be the case may be seen by considering Figure 2 and assuming that the wavefronts W_A and W_B come from points on opposite extremities of the object. As the angular separation of these points decreases, the wavefronts W_A and W_B become more nearly parallel, and the fringes F_1, F_2, F_3 .... become more widely spaced. In the limit, if the angular extent of the object is zero, (i.e. if the object is simply a point source), then no speckle-pattern component is produced and no scattering of the reconstructing light beam occurs from this cause. It can be shown[18c,89] that the angular extent of the flare components is up to twice the angle subtended by the object at the hologram. In order to reduce the angular extent of the flare component, the effective size of the object may be reduced by illuminating only a portion of it at any one time and scanning this illuminated portion over the whole object (see Section 4.2.2). Alternatively, because the spatial frequencies involved in the recording of the speckle pattern are relatively low compared with those present in the holographic recording, techniques which selectively record the latter range of spatial frequencies may be used (see Section 4.3.2 and 4.3.4).

The angle between the wavefronts reaching a given point in the interference pattern can be restricted by placing an aperture between the diffusely-reflecting object and the point in the interference pattern under consideration, with the result that the scale of the resulting speckle pattern becomes greater (i.e. the speckle pattern becomes coarser) as the size of the aperture is reduced or the distance between the aperture and the plane of observation is increased. This effect occurs whenever a lens is used to form an image of a diffuse object illuminated with coherent light, the scale of the interference pattern being determined by the aperture (f-number) of the lens (in fact, the scale of the speckle pattern is equal to the radius of the diffraction-limited spot (Airy disc) which would be produced at the focus of the lens[28a] if illuminated by collimated coherent light of the wavelength under consideration). The scale of the visually-observed speckle pattern is thus determined by the aperture of the lens of the eye, and is independent (except for

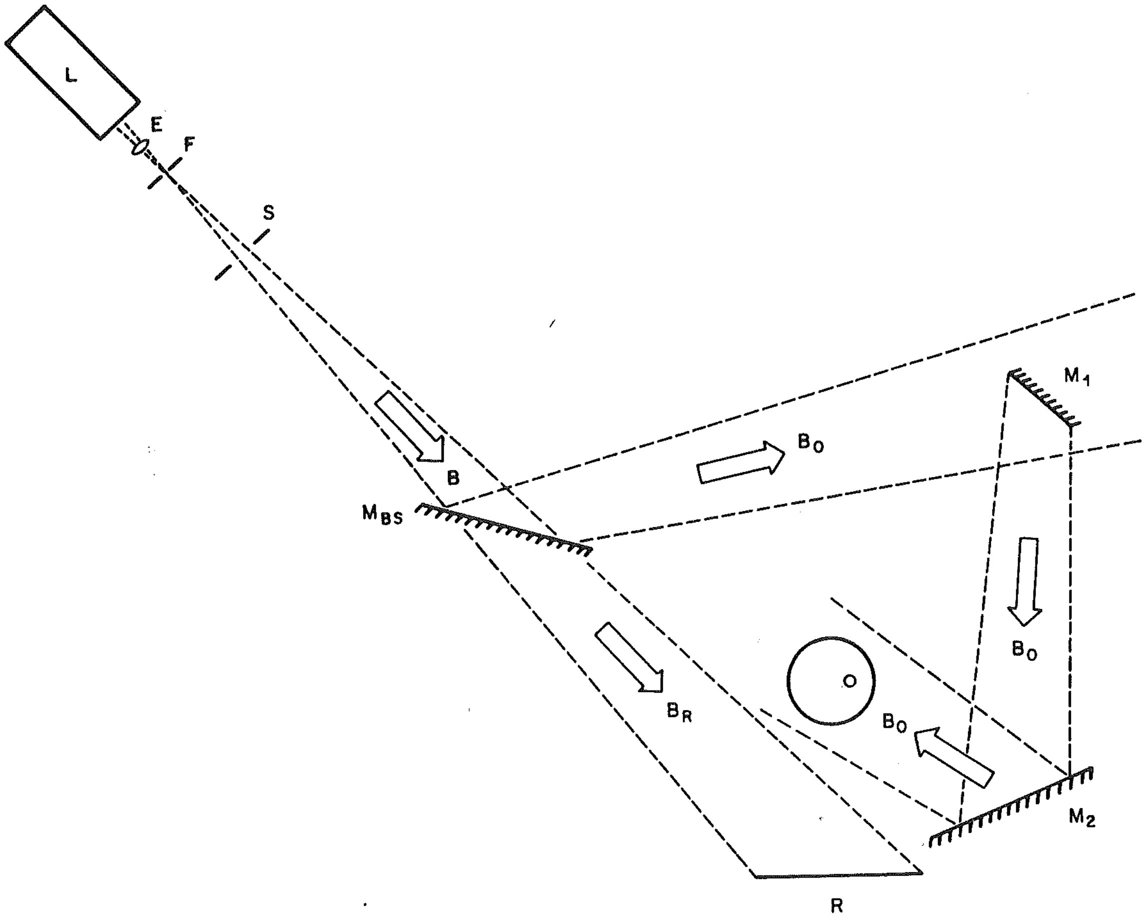

Fig. 10 - Arrangement for making a hologram of a solid object

L – laser
E – Expanding lens
F – Pinhole filter
S – Shutter
B – Expanded beam
M_{BS} – Beam-splitting mirror
B_R – Reference beam
R – Recording medium
B_o – Object – illuminating beam
M_1, M_2 – Mirrors
O – Object

objects subtending a very small angle) of the object size Stroke[19a] has stated that in photography the use of a lens stop numerically lower than about f/10 gives rise to a photographic image virtually free of speckle pattern (i.e. the scale of the speckle pattern is finer than that of the film grain).

4. Methods and materials

4.1. The basic holographic system

4.1.1. Practical considerations

A typical practical arrangement for making a hologram of a solid object is shown in Fig. 10 (see also Fig. 6, Section 2.2). Light from the laser (L) is formed into a divergent beam (B) by means of the short focal-length 'expanding' lens (E) and is divided into two components by a partially-reflecting beam splitting mirror (M_{BS}). One component (B_R) falls directly onto the recording medium (R) and forms the holographic reference beam: the other component (B_O) is deflected by a suitable mirror arrangement (M_1, M_2) so as to illuminate the object (O) from the required direction. A shutter (S) controls the duration of exposure of the recording medium.

Interference fringes are formed whenever beams of coherent radiation, originating from the same source but differing in path length* or direction of travel, occupy the same volume of space. These fringes will be recorded by the recording medium if this also occupies the common volume. As well as the 'wanted' fringes formed from light in the object and reference-beam paths, unwanted reflections from the surfaces of the optical components in the recording system, or from blemishes on such surfaces, also give rise to fringe patterns by interference with the reference or object illuminating beams. Since the differential path lengths involved in the generation of these fringe patterns often change only slowly with the position of observation, these patterns have a relatively coarse structure and may give rise to obvious shading effects on the recording medium which impair the quality of the reconstructed holographic image. Apart from the fringes produced by blemishes on

* Provided that the path length does not exceed the coherence length of the radiation (see Section 1).

the mirror surfaces controlling the expanded beams,* two sources of spurious interference patterns are of particular importance:—

(a) Reflections (specular or scatter from blemishes) off surfaces of the individual components of the expanding lens (E in Fig. 10).

(b) Reflection off the 'unsilvered' surface of the beam-splitting mirror (M_{BS} in Fig. 10).

Light passing straight through the expanding lens converges onto a focal point and subsequently diverges to form the expanded beam. Light emerging from the lens after having undergone internal reflection may also converge, but to a different focal point. A small pinhole placed at the focal point corresponding to the wanted beam will permit the light forming this beam to pass, but will obstruct the scattered light emerging from the lens, and thus eliminate the spurious interference fringes. This process is termed 'spatial filtering': the pinhole filter (F in Fig. 10) typically has a diameter of about 20 μm. The unwanted reflection from the beam-splitting mirror may be suppressed by arranging that the angle of incidence of the light onto the mirror corresponds to the Brewster angle, when the appropriate choice of polarisation will suppress the reflection from the unsilvered surface. Another method is to use a wedge-shaped mirror, so that light is reflected from the 'unsilvered' surface in a direction away from the holographic recording medium. Alternatively, the beam-splitting may be carried out in the unexapnded laser-beam path, and separate expanding and spatial filtering arrangements used for the reference and the object-illuminating beams.

A hologram may be made of an object in transmitted light by appropriate arrangement of the object-illuminating beam system. A diffusing screen placed behind the object ensures that light from each element of the object can contribute to the formation of the recorded interference pattern over the whole area of the hologram. The advantages of such a diffusing arrangement[6] have been described in Section 1.

Image reconstruction is carried out using a beam of light having identical characteristics to the reference beam used during recording (for example, by placing the hologram in the position R in Fig. 10, the object, mirrors and shutter being omitted). As long as this identity is observed, there is theoretically no restriction on the properties of the reference and reconstruction beams: they may be collimated or more or less strongly convergent or divergent, or alternatively may be random in character (by insertion of a diffusing screen, for example). The wanted reconstructed image occupies the same position in space, relative to the hologram, as did the original object during the recording process. If the identity of the reference and reconstruction beams is not strictly observed, some distortion of the reconstructed image occurs, the amount of distortion depending on the nature of the differences between the two beams.[18]

4.1.2. Multiple exposures

If a hologram is made of an object consisting of an array of bright points in an otherwise dark background, interference patterns will be generated from light emanating from each pair of points in the object (see Section 2.1). These unwanted patterns are recorded along with the wanted patterns generated from light emanating from any one point and the reference beam, and during image reconstruction give rise to spurious images. The process of simultaneously recording a number of discrete object points has been termed 'coherent superposition' by Smith.[18] The magnitude of the spurious images produced by coherent superposition may be reduced by arranging that the intensity of the reference beam is large compared with the intensity of the light from any object point. Complete elimination of the spurious images may be obtained by ensuring that the unwanted interference patterns are not generated: this may be achieved by using a process of 'incoherent superposition' in which a number of holographic exposures are made, each consisting of only one object point together with the reference beam. It can however be shown[18,90] that, if the total exposure of the recording medium produced by the successive exposures of the incoherent superposition process is equal to that occurring in the single exposure of coherent superposition, then the diffraction efficiency* for an individual image point is proportional to N^{-1} in the case of coherent superposition, and to N^{-2} in the case of incoherent superposition, the quantity N being in each case the total number of image points.[18d] For a given number of image points, the use of coherent superposition will therefore give a hologram having a diffraction efficiency greater by a factor of N than in the case of incoherent superposition. This consideration imposes a restriction on the use of incoherent superposition as a method of elimination spurious images in holographic reconstruction, particularly in the case of large values of N.

In the case of volume holograms (see Section 2.3) the holographic image is not reconstructed if the angle of incidence of the reconstruction beam differs significantly from that of the reference beam used when making the hologram. The spread of reconstruction-beam angles over which an image is produced decreases as the number of recorded holographic interference fringes involved in image reconstruction increases: thus this spread of angles decreases both as the thickness of the recording medium is increased and as the reference-beam angle increases. Smith[18] has derived curves showing the change in reconstruction-beam angle required to extinguish the reconstructed image, expressed as a function of both reconstruction-beam angle and recording-medium thickness.[18e] It is therefore possible to expose successively a number of holograms, each such hologram being made with a different reference-beam angle, and reconstruct each holographic image independently of all the others, by suitable choice of reference- and reconstruction-beam angles of incidence. For a recording medium with limited exposure range, as described above, it can be seen that the diffraction efficiency of each of M holograms in such a multiple-exposure system will be smaller by a factor M^2 than the diffraction efficiency of a single hologram out of this set, exposed so as to exploit the whole exposure range. (The characteristics of each of the set of M holograms is assumed to be identical: for example, the object in each case consists of N point sources.) This consideration again imposes a limit on the number of separate holograms which can be superimposed. However, if the holographic fringes are recorded as refractive index changes in the recording medium and the number of such fringes involved in the image reconstruction process is very large, a situation can occur in which a high diffraction efficiency is obtained even though the change is refractive index produced in the medium by the holographic fringe pattern is extremely small compared with the total possible change in refractive index under full exposure conditions (in other words, if only one hologram is recorded on the medium. the highest possible diffraction efficiency is obtained under exposure conditions which are much less than the maximum permitted by the characteristics of the medium). In such a case the characteristics of the medium are better exploited if a succession of holographic exposures is made, each exposure being such as to produce satisfactory diffraction efficiency. Because of the large number of fringes involved in image reconstruction the tolerance in reconstruction-beam angle of incidence will be very small, and it may be possible to record a large number of separate holograms in one region of the recording medium.

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* In common with all optical work involving non-diffuse illumination, the effect of such blemishes cannot be eliminated and attention to the quality of cleanliness of such surfaces is essential.

* defined on p. 6.

4.2. Alternative holographic arrangements

4.2.1. Heterodyne systems

Holographic systems have been described[36,37,38] in which the frequency of the radiation in the reference beam differs from that in the object-illuminating beam. In such 'temporally modulated' or 'heterodyne' systems the interference pattern is no longer stationary (see Section 2.1) and time exposure methods cannot be used to record the pattern. If, however, the holographic recording medium (R in Fig. 10) is replaced by a photoelectric receptor (P in Fig. 11) in front of which is placed an opaque plate containing a pinhole (H), its output signal will contain a 'beat-frequency' component having a frequency equal to the frequency difference between the object-illuminating (B_0) and reference-beam (B_R) components of the incident radiation. If, now, the pinhole is scanned in a raster-like fashion over the whole area of the photoelectric receptor, other components will appear in its output signal, having frequencies corresponding to the spatial carrier frequency of the holographic system (see Section 2.2) and to the spatial sidebands which carry the information about the object (O in Fig. 11). By suitable choice of reference-beam direction (i.e. by the use of an 'on-axis' arrangement) the frequency of the spatial carrier may be made zero, but the beat-frequency component will remain. The output signal from the photoelectric receptor is made to modulate the intensity of a spot of light which is scanned in synchronism with the motion of the pinhole: this spot of light is imaged onto a sheet of light-sensitive material, which when processed becomes the final hologram of the object. The beat-frequency signal component will give rise, on the hologram, to a recorded spatial carrier. With appropriate choice of reconstruction-beam angle, the holographic image can then be reconstructed in the usual manner. The advantage of this heterodyne method is that, with the elimination of the original spatial carrier component, the sidebands surrounding the zero-order component (see footnote on p.6) are also eliminated, and light is not diffracted away from the straight-through direction of the reconstructing beam. The (spatial) frequency of the spatial carrier on the final hologram need only be high enough to separate the reconstructed image from the straight-through direction of the reconstructing beam, thus reducing the resolution requirements of the recording medium. This reduction in required resolution is also important when the transmission of holographic information by a television system is considered.[89]

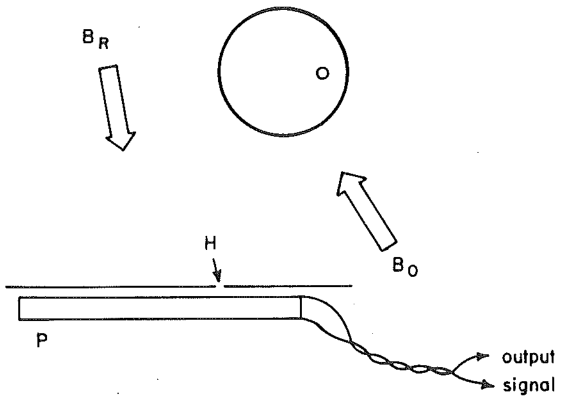

Fig. 11 - Heterodyne holographic system

P — Photoelectric receptor
B_0 — Object — illuminating beam
H — Scanning pinhole
B_R — Reference beam
O — Object

4.2.2. Light-beam scanning techniques

Instead of using a scanning pinhole in front of the photoelectric receptor of the system described in Section 4.2.1, the entire area of the receptor may be exposed[36] but the reference beam, in the form of a thin pencil of light, scanned over it. The effective output signal from the receptor will come from the region on its photosensitive surface at which the reference and object beams interfere and produce an alternating component due to their relative motion: light falling on other areas of the photosensitive surface produced only a constant 'd.c.' output-signal component which may be suppressed by suitable filter circuits. It should however be noted that in practical terms, an increase in the d.c. output-signal component will be accompanied by an increase in the electrical noise component. One method of reducing this d.c. component would be to arrange that the pencil reference beam remain fixed in direction and the light from the object be subject to the scanning process (without geometrical distortion): in this case the surface area of the photoelectric receptor need only be great enough to intercept the thin reference beam.

The range of spatial frequencies present in the 'noise' sidebands surrounding the zero-order reconstruction component (see footnote on p.6) is determined by the magnitude of the angle subtended at the hologram by the extremities of the object: thus a large object gives rise to higher noise spatial frequencies, and therefore greater scatter of the light from the straight-through direction, than does a small object. This principle is used in a technique[39] which avoids the generation of all but the lowest spatial-frequency noise sidebands while using object-illuminating and reference beam radiation of the same frequency. Only a very small region of the object is illuminated at any one time, thus reducing the size of the object to that of the illuminated area: the effect of overall object illumination is provided by scanning this small area of illumination over the whole object area. This technique amounts to making many successive holograms of the individual illuminated object areas, and the diffraction efficiency (see Section 2.2) of the resulting composite hologram will be lower than for a conventional hologram in which the whole object is simultaneously illuminated (see Section 4.1.2).

4.2.3. Space coding

Rays of light from the object which make only a small angle with the reference-beam direction will give rise to patterns of low spatial frequency on the hologram. In one realisation of the space coding system[40] a 'coding plate' (C in Fig. 12) placed near to the line of the reference beam (B_R) reflects light from the object onto the recording medium (R). The coding plate has diffuse reflecting properties so that some light from any given point on the object is scattered so as to reach the recording medium along a direction making a small angle with the reference beam. The size of the coding plate is such that no ray of light from it can make a large angle with the reference beam: thus each object point is represented on the hologram by a pattern of low spatial frequency. Image reconstruction is carried out (Fig. 13) using a beam of light (B_R') of identical geometry to the original reference beam, but travelling in the opposite direction. Light diffracted by the hologram is diffusely reflected by a coding plate identical to and in the same position as the one used in forming the hologram, and the image (I) is reconstructed by light scattered from the plate. Other components of scattered light produce unwanted background illumination, which may be reduced by appropriate choice of the properties of the coding-plate. In one variant of the system, termed 'space-time multiplexing',[41] a successing of holograms is recorded, the coding plate being moved between each exposure: during image reconstruction the corresponding movement of the coding plate is sufficiently rapid to produce the illusion of complete image reconstruction, persistence of vision providing the necessary integration.

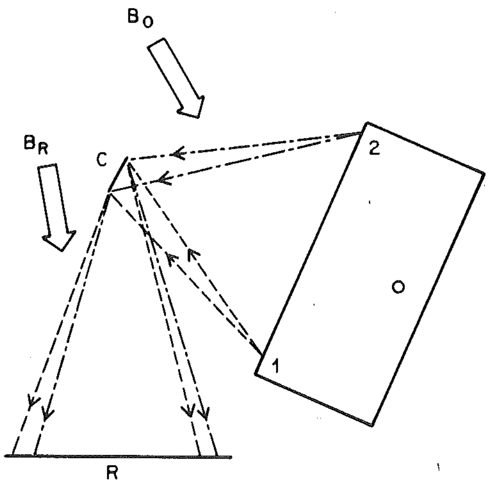

Fig. 12 - Holographic recording system using space coding technique

– – – – – – Light from point '1' of object
–·–·–·–· Light from point '2' of object
R — Recording medium
C — Coding plate (see text)
O — Object
B_O — Object — illuminating beam
B_R — Reference beam

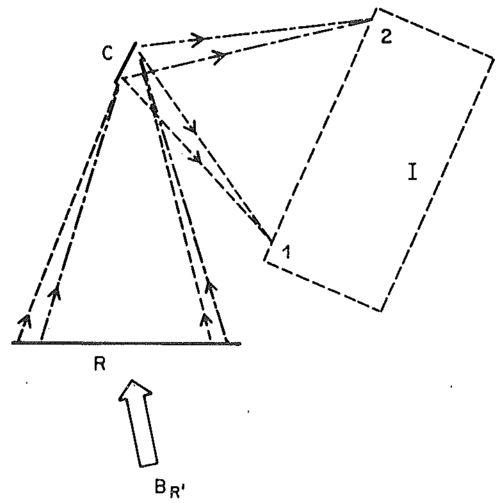

Fig. 13 - Holographic reconstruction using space coding technique

– – – – – – Diffracted light reconstructing point '1' of image
–·–·–·–· Diffracted light reconstructing point '2' of image
R — Processed recording medium (hologram)
C — Coding plate (see text)
I — Image
B_R' — Reconstruction beam

In another (and historically earlier) coding system[42] a fly's-eye lens is used to form an intermediate coded image of the object on photographic film, using white light. A real aerial image of the object can be obtained by illuminating the processed film from the reverse direction with white light and with the fly's-eye lens in the same relative position to the film. This image will, however, be pseudoscopic (see Section 1). If a hologram is made using this aerial image as an object (and, of course, using coherent illuminating radiation), a virtual image of the original object with conventional three-dimensional properties will be formed. A recent proposal[100] again uses a fly's-eye lens but in this case a hologram is formed of the light emerging from the lens: in principle coding plates of forms differing from a fly's-eye lens can therefore be used, since the plate need not form a multiplicity of images as is the case with a lens of this type. A pseudoscopic image is again formed, due to the reversal of the direction of light during image reconstruction, and this disadvantage is again overcome by making a second hologram.

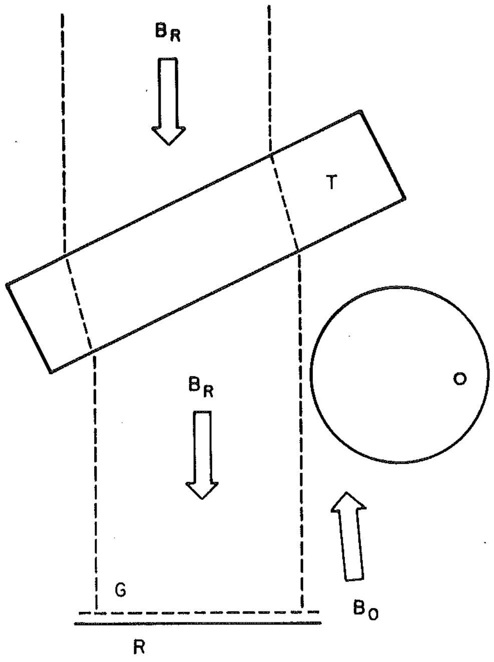

Fig. 14 - Holographic recording system using synthesised carrier technique

R – Recording medium
G – Grating
T – Phase changer (rotating transparent plate)
O – Object
B_O – Object – illuminating beam
B_R – Reference beam

4.2.4. Synthesised carrier systems

In the heterodyne system of hologram formation (see Section 4.2.1) the phase of the radiation in the reference beam continuously changes relative to that of the object-illuminating beam. By using suitable recording arrangements this continuous phase change may be used to produce a spatial carrier component on the recorded hologram, the conventional spatial carrier being suppressed by the use of an 'on-axis' recording arrangement. In a synthesised carrier system[43] an approximation to this same effect is obtained by using radiation of the same frequency in both paths of an on-axis holographic arrangement, but arranging that the relative phase of the reference-beam radiation may be altered* by known amounts (Fig. 14). A grating (G) is placed immediately in front of the holographic recording medium so as to obscure all but relatively narrow strips of the medium: the period of this grating determines the spatial frequency of the synthesised carrier. Narrow strips of the recording medium are thus exposed using reference-beam radiation of a certain relative phase. The phase of the reference-beam radiation is then changed by a certain amount, the grating moved along a line normal to the stripe pattern so as to expose a contiguous narrow strip of the recording medium, and a second holographic exposure is made. The process is continued, successive strips of the medium being exposed with further equal phase changes of the reference beam, such that when the originally-exposed strips are again available for exposure the reference-beam phase has been changed by a whole wavelength of the radiation (however, exposure of the recording medium is complete when each strip has been exposed once only). It has been shown[44] that at least three such successive exposures are required, phase shifts of 120 degrees being introduced between each exposure.

4.2.5. Holography using radiation of limited coherence

Although the use of highly coherent radiation greatly enhances the ease with which holograms may be produced, it is possible to produce holograms in incoherent radiation, using conventional 'monochromatic' light sources (sources emitting radiation in narrow spectral lines: for example, a mercury discharge). Arrangements[18,28,45] giving a system of achromatic interference fringes are used for this purpose. In such arrangements the phase difference between components of radiation arriving at a location by way of two different beams is independent of wavelength. One of the beams illuminates the object (a thin transparency) while the other acts as an off-axis reference beam. It should be remembered that Gabor's original 'on-axis' work[1,2,3] was performed using such light sources.

Another method proposed for making holograms in white light[46] is to use a conventional photographic camera focussed onto the object, but to move the camera continuously while varying the transmission of the lens in accordance with a known law. A point on the object gives rise, on the processed photographic plate, to a line of varying transmission which acts as a diffraction grating and enables a holographic image to be obtained, using coherent radiation during the reconstruction process.

4.2.6. Computer-generated holograms

The amplitude and phase of the radiation from a diffusely-reflecting or diffusely-transmitting object may be computed at some plane a certain distance from the object. A plate may then be prepared from the computed information which will act as a hologram when illuminated with coherent radiation. One such device is the Kinoform,[47] in which a phase hologram is prepared from the computed information. It is claimed that all the incident radiation may be diffracted into the wanted image-forming component.

4.3. Materials for use as holographic recording media

4.3.1. General

The factors which must be considered when assessing a particular recording medium are:–

(a) The exposure characteristics of the medium itself,[18] including resolution, actinic sensitivity both in absolute terms and as a function of wavelength, reciprocity between exposure time and intensity,[48] and transfer characteristic.

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* In Fig. 14 rotation of the transparent plate T about an axis normal to the plane of the diagram produces the required phase change by altering the path length through the transparent medium.

(b) The type (surface or volume: see Section 2.3) of hologram produced.

(c) The quality of the holographic image[18] in terms of diffraction efficiency, resolution, geometrical distortion, transfer characteristic and noise characteristics (including shading, vignetting, spurious striations etc., 'graininess' and veiling glare).

(d) The properties of the information-storage mechanism, including the permanence of the holographic record and the possibility of record erasure and re-usage of the medium.[99]

(e) The mechanical and other physical properties of the medium itself, and the nature of the processing required after exposure.

(f) The availability and cost of the material.

In general terms, a suitable medium should be capable of exposure using a laser of moderate power, should give high diffraction efficiency (i.e. should produce a phase hologram), should give a reconstructed image free from excessive veiling glare, should retain the holographic information indefinitely and should require only very simple processing after exposure. A detailed specification of the required properties of the medium would depend upon the particular application for which it was intended. All the materials considered in the following sections involve direct exposure to the incident radiation. Systems involving the generation of a hologram upon receipt of an electrical signal are not considered (since there are none capable of giving a reconstructed picture of a quality comparable with present-day television displays): holographic television displays are, however, discussed elsewhere.[89]

4.3.2. Photographic emulsions

Photographic plates and films[48] are a long-established method of recording light intensity distributions and provide the most obvious method of recording holographic information. Most conventional film stocks, however, do not possess sufficiently high resolution for recording the interference patterns associated with off-axis diffuse-illumination holography (patterns are produced with spatial frequencies of the order of 2000 cycles/mm) and, at the same time, sufficient sensitivity at the wavelength (632·8 nm) emitted by the commonly-used helium-neon laser. Special 'holographic' film stocks[93] are now available which possess adequate resolution and sensitivity* to helium-neon radiation. However, with the greater availability of medium-power (e.g. up to about 100 mW) lasers emitting in the near ultra-violet or blue spectral range, the requirement of sensitivity to long-wavelength radiation is no longer so important.

Phase holograms can be produced in photographic emulsions by bleaching processes, in which the metallic silver present in an exposed and developed hologram is converted into a transparent silver salt having a higher refractive index than the surrounding emulsion material. This technique was first described by Cathey[49] in 1964, and has since been studied in great detail.[18,50–56]

Various methods for carrying out the bleaching processes have been described,[50,52,53,55–58] the purpose usually being to maximise the refractive-index difference between exposed and unexposed areas of the emulsion, and so form an efficient volume hologram. As well as local changes in refractive index, the surface of the emulsion becomes deformed and a 'relief image' is produced,[59] forming a surface hologram form which image reconstruction[60] may be obtained. It is, however, generally considered preferable to suppress the effects of the relief image as far as possible (for example, by using conventional immersion techniques), as this image consists mainly of the holographic patterns of relatively low spatial frequency corresponding to the 'noise' components (see footnote on p.6) which scatter light from the straight-through direction of the reconstructing beam without contributing to the holographic image. In a recently-described technique ('reversal bleaching'),[55,56] regions of high refractive index in the emulsion are made to correspond with the thinner regions of the emulsion produced by the surface deformation effects, thus tending to cancel out the effect of the low spatial frequency components as far as their effect on the phase of the radiation transmitted by the hologram is concerned. This technique leads to a greater reduction of light scatter compared with the use of immersion techniques.

In summary, it may be said that the principal disadvantages of photographic emulsions as a holographic recording agent are the non-reversible nature of the photographic process and the involvement of the developing, bleaching and drying processes after exposure. The granular nature of the photographic process is to some extent responsible for introducing veiling glare into the reconstructed image, although the presence of low-spatial-frequency recorded interference patterns has been cited[56] as the principal reason for veiling glare. Nevertheless, the advent of medium-power lasers emitting in the ultra-violet or blue spectral range, and the availability of high-resolution emulsion stocks on flexible bases, makes photographic film a very strong contender as a holographic recording medium.

4.3.3. Dichromated gelatin and photoresists

A thin layer of gelatin on a supporting substrate may be made sensitive to radiation by bathing in a dichromate solution.[61,88] The peak sensitivity occurs at approximately 380 nm and extends to about 540 nm. The sensitised gelatin hardens on exposure to the radiation, and a surface relief pattern may be obtained[61] after exposure by immersion in warm water followed by a drying process which includes washing with an alcohol. Similar effects may be obtained using photoresist materials:[63,64] these also have peak sensitivities in the near ultra-violet and are processed by immersion in (or spraying with) the appropriate developer. Changes in refractive index in the undeveloped photoresist[88] have also been reported, which could permit the production of volume holograms. The principal advantage of these media is the very high resolution that they exhibit, as they are effectively homogenous (unlike photographic emulsions, which have a granular structure of the order of magnitude of the wavelength of light): the diffraction efficiency is therefore high even for recorded interference patterns of very high spatial frequency. A further advantage of photoresist materials is their extreme dimensional stability during processing: this is attributed[64] to the fact that water is not a constituent of the developing agent. Disadvantages include the rather low actinic sensitivity of the materials to the radiation (about 100 – 10^5 times less sensitive than photographic-emulsions[66]) and the restricted useful wavelength range. In this connection it may be noted that the high sensitivity of photographic emulsions and the high diffraction efficiency of dichromated gelatin may be combined[62,65,66,94] by first recording the hologram on photographic emulsion, developing and bleaching the emulsion, and then treating the bleached hologram with a dichromate (thus 'dichromating' the gelatin on the photographic emulsion) and re-illuminating it with coherent ultraviolet light. Diffraction occurs due to the original holographic record in the bleached hologram, and this diffracted radiation interferes with the 'straight-through' component of the incident radiation, resulting in the re-recording of the hologram in the dichromated gelatin.

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* Very approximately, the sensitivity of a 'holographic' film stock is of the order of 1 μJ/mm^2.

Since a surface relief pattern is obtained on developing dichromated gelatin or photoresist holograms, surface holograms are in general produced which are not subject to Bragg angle effects (see Section 2.3).

By using photoresist materials in their conventional manner (i.e. to form a mask corresponding to a light pattern or image through which the surface of a substrate may be selectively etched), surface holograms may be formed on metal surfaces. Such holograms are very durable and in one application[91] can be used to emboss the holographic pattern onto a material that is not itself photosensitive. A holographic image may also be obtained by reflection[60] from the embossed metal surface.

4.3.4. Thermoplastic photoconductive sandwiches

A material is said to be thermoplastic if it may be plastically deformed (so that the deformation remains after the force causing it is removed) above a certain 'softening' temperature, but has normal elastic properties below this temperature. For use as a holographic recording medium[62,67,68,95] the thermoplastic material (T in Fig. 15) is made the upper layer in a thin 'sandwich' arrangement: it is underlaid with a photoconductive layer (P) which is in turn underlaid with an earthed transparent ohmic conducting layer (C). The sandwich structure is supported on a suitable transparent substrate (S). In use, the ohmic conducting layer is earthed and the cool (i.e. below the softening temperature) thermoplastic surface is charged electrostatically without exposure to radiation. In this condition the photoconductive layer has low and uniform conductivity and the electric field across the thermoplastic layer is uniform. When the medium is exposed to the holographic interference pattern the point-to-point conductivity of the photoconductive layer is related to the corresponding intensity of radiation in the interference pattern. The electric field across the thermoplastic layer therefore also varies from point-to-point in relation to the intensity variations in the interference pattern. While this condition persists the thermoplastic layer is heated momentarily to above the softening temperature, when local deformation of the surface under the influence of the electric field takes place: the amount of deformation is therefore also related to the intensity variations in the interference pattern and a surface hologram is produced. On cooling the thermoplastic layer below the softening temperature the surface deformations are 'frozen' into the material and a permanent holographic record is obtained. This record can, however, be erased by re-heating the thermoplastic layer above the softening temperature in the absence of an electric field.

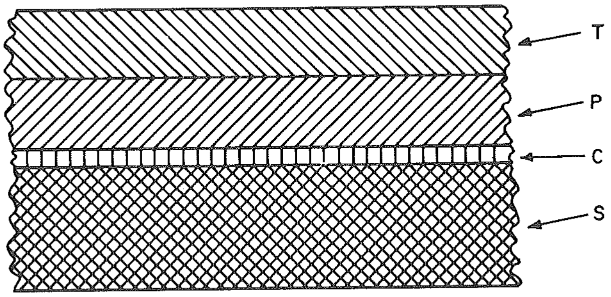

Fig. 15 - Thermoplastic photoconductive sandwich

T – Layer of thermoplastic material
C – Ohmic conducting layer
P – Photoconductive layer
S – Substrate

It has been shown[69] that in thermoplastic recording systems the surface deformation proceeds more rapidly for a range of spatial frequencies than for others outside this range. This effect is termed 'quasi-resonance', the quasi-resonant spatial frequency depending on the thickness of the thermoplastic layer and the electric field applied across it. In a holographic recording system the reference-beam angle can be adjusted so that the spatial carrier frequency (see Section 2.2) corresponds to the quasi-resonance frequency. As the filtering introduced by the quasi-resonance effect suppresses spatial-frequency components (see footnote on p.6) which give rise to scattering of the reconstructing-beam radiation, such scatter is minimised, particularly as the material itself is homogenous (see Section 4.3.3).

The heating of the thermoplastic layer may be accomplished in several ways. The use of a stream of hot air[67] or the passage of current through the ohmic conductor[68] have been described: other methods are also possible.

The system described by Urbach and Meier[17] showed resolution extending up to at least 1000 cycles/mm and a spectral sensitivity including the helium-neon laser radiation of wavelength 632·8 nm. The actinic sensitivity at this wavelength was approximately an order of magnitude greater than for high-resolution 'holographic' photographic emulsions. Improvements on this system could probably be obtained by a different choice of thermoplastic and photoconductive materials. A surface hologram is produced which is not subject to Bragg angle effects.

4.3.5. Photo-polymerisation

The term 'polymerisation' describes a chemical reaction in which a number of molecules of a substance (known as the 'monomer') combine to form a single molecule of another substance (known as the 'polymer'). The physical and chemical properties of the polymer may differ markedly from those of the monomer from which it is derived: to take a well-known example, the gas ethylene polymerises to form the solid polyethelene or 'polythene'. Monomers are usually stable substances which can exist indefinitely in their monomeric form, and energy has to be supplied, usually in the presence of a catalyst, to induce the polymerising reaction. In the present case of photo-polymerisation,[70,71] the energy is supplied in the form of electromagnetic radiation: the monomer is a liquid, while the resulting polymer is a solid.

The holographic recording medium is prepared by mixing the monomer with a 'binder' material which may be applied as a thin coating onto a transparent substrate. This coating also contains an 'initiator' which acts as the catalyst and causes polymerisation to occur on exposure to radiation. The process of exposure and processing described by Colburn and Haines[71] proceeds as follows:—

1. The medium is exposed to the holographic interference pattern and some polymerisation occurs, to an extent depending on the local intensity of the radiation within the pattern.

2. After holographic exposure, spatial redistribution of the remaining monomer occurs. The concentration of monomer in regions of high exposure is lower (because the monomer has been polymerised) than in regions of low exposure, and monomer molecules diffuse from regions of high concentration into regions of low concentration, so as to tend to equalise the concentration values. Thus monomer molecules diffuse into the exposed regions in which some polymerisation has already occurred, and unexposed regions in which polymerisation has not occurred are depleted of monomer molecules. This process takes place in the absence of incident radiation.

3. The medium is re-exposed to uniform illumination, and all the remaining monomer is polymerised. The final point-to-point concentration of polymer depends on the corresponding concentration of monomer after the completion of the redistribution process (Stage (2) above) and is thus greatest in regions of highest holographic exposure. The refractive index of the polymer differs from that of the binder material and a volume phase hologram is thus formed: surface effects are also apparent, particularly at low spatial frequencies.

The hologram resulting from the process described above shows reasonably good diffraction efficiency (a maximum of 10% at 1000 lines/mm): if surface relief effects are eliminated by immersion in an index-matching material, the effect of low spatial frequencies is almost entirely eliminated and scatter of the reconstructing beam correspondingly reduced (see footnote on p.6). As the material is homogeneous, scatter from grain structure is not present. The spectral sensitivity of the medium is at a maximum at about 360 nm but can be made to extend up to about 510 nm by suitable choice of initiator material, with a loss in sensitivity of about an order of magnitude. Comparison of the absolute actinic sensitivity of the medium at 360 nm with that of a 'holographic' photographic emulsion at 632·8 nm shows the photo-polymerisation medium to be about an order of magnitude lower in sensitivity.

In the process described by Jenney[70] the re-distribution of monomer following holographic exposure does not take place, the local degree of polymerisation simply depending on the intensity of radiation at that point. The materials used in this process are sensitive to helium-neon radiation (632·8 nm). Subsequent to holographic exposure the hologram is 'fixed' by illuminating with ultra-violet light: this prevents further formation of polymer when the hologram is subsequently illuminated. The process gives rise to considerable thickness variations in the exposed material, and surface holographic effects predominate in image reconstruction: some volume effects due to refractive index changes are also apparent. The actinic sensitivities of the various substances described by Jenney are all lower (at 632·8 nm) as compared with the maximum sensitivity (at 360 nm) of material used by Colburn and Haines.

4.3.6. Single crystals of electro-optic materials

The refractive index of many crystalline materials depends on the electric field in which the material is situated.[28] In some (ferroelectric) materials[72] this electro-optic effect is particularly marked. Some of these materials also exhibit an effect known as 'charge-trapping'[73,96] in which charge carriers (electrons or 'holes') are localised by electric fields produced by defects in the lattice structure of the crystal.[74] Application of energy to the crystal structure may excite a charge carrier out of its trap and it can migrate through the crystal structure until recaptured by another trap.[73,75] For use as a holographic recording medium, the holographic interference pattern is formed within a single crystal of the material, which is assumed to be nearly transparent to the radiation. A small fraction of the energy in the radiation is absorbed by the crystal, the amount of absorbed energy in a small volume of the crystal depending on the local intensity of the interference pattern. This energy excites charged carriers out of their traps, and the carriers migrate for a short distance until 'captured' by another trap. Local variations of the internal electric field are set up, which in turn give rise to local variations of refractive index due to the electro-optic effect: thus refractive index changes are produced which relate to the intensity variations in the interference pattern. In some cases[76] an external electric field is applied to the crystal during hologram formation, while in other cases[77] no such field is present.

Chen et al[77] have calculated that refractive index changes of 2×10^{-5} are produced: this gives a diffraction efficiency of about 40%. Spatial frequencies of up to 1600 cycles/mm can be recorded with this diffraction efficiency, the use of much higher spatial frequencies being possible with reduced efficiency. Very high radiation intensities (about 1 J/mm^2 or about a million times the intensity required for photographic emulsions) are required for exposure.

In the system described above, no processing occurs after holographic exposure of the medium. Radiation falling on the medium after such exposure causes further charge redistribution to occur, resulting in the decay and eventual erasure of the recorded holographic information. Complete erasure is obtained on heating the medium. A system recently described by RCA,[78] using single crystals of lithium niobate or barium-sodium niobate, enables a permanent holographic record to be made. Charge redistribution initially takes place within the crystal as described above, but after holographic exposure the crystal is heated to about 100°C. At this temperature migration of ions takes place under the influence of the holographic charge pattern. On cooling the crystal these ions are immobilised and themselves provide a charge pattern (and therefore a refractive index variation) which is not erased when the crystal is exposed to radiation during holographic image reconstruction. The holographic information can be erased by again heating the crystal. The actinic sensitivity of this process is claimed to be about 500 times greater than previous single-crystal systems, and a potential digital storage capacity of 10^{12} bits/cm^3 is said to be available.

4.3.7. Ferroelectric photoconductive sandwiches

The ferroelectric material bismuth titanate exhibits an unusual electro-optic property.[79] Light travelling through the crystal along a certain crystallographic axis (the 'b axis') is plane polarised in one of two directions inclined at approximately 40 degrees to each other. If an electric field is applied along another crystallographic axis (the 'c axis') the plane of optical polarisation is defined as one of these two possible directions. This plane of polarisation persists when the electric field is removed. If, however, the electric field is reversed, the plane of polarisation changes to the other of the two possible directions, and this condition again persists when the electric field is removed. For use as a holographic storage medium[62,80,81] thin layers of bismuth titanate (B in Fig. 16) and a photoconductor (P) are sandwiched between transparent ohmic conducting electrodes (C$_1$ and C$_2$), the orientation of the crystals in the bismuth titanate layer being appropriately chosen.[80] The sandwich structure is supported by a transparent substrate (S). A potential of reversible polarity may be applied between the ohmic electrodes by means of a switch (Sw). Initially the polarity of the potential applied across the sandwich is made to correspond to the 'erase' condition and the material is uniformly illuminated: thus the optical polarisation plane is defined as one of the two possibilities. The uniform illumination is then removed and the material is exposed in the holographic system using the reversed 'write' polarity condition. The optical polarisation plane changes to the other of the two possibilities only in the bright regions of the holographic interference pattern, where the conductivity of the photoconductive layer is high. After exposure the applied potential is removed and the holographic record is then permanently stored until the 'erase' process is repeated. Reconstruction of the holographic image is carried out in light of appropriate polarisation. The maximum change in direction of optical polarisation is obtained along an axis normal to the direction of application of the electric field. In the thin sandwich structure this direction is contained in the plane of the material and is therefore impossible to achieve. Satisfactory reconstruction can, however, be obtained if a non-normal reconstructing beam[81] is used; the change in direction of optical polarisation is then less than the maximum value and depends on the angle of incidence of the reconstructing beam.

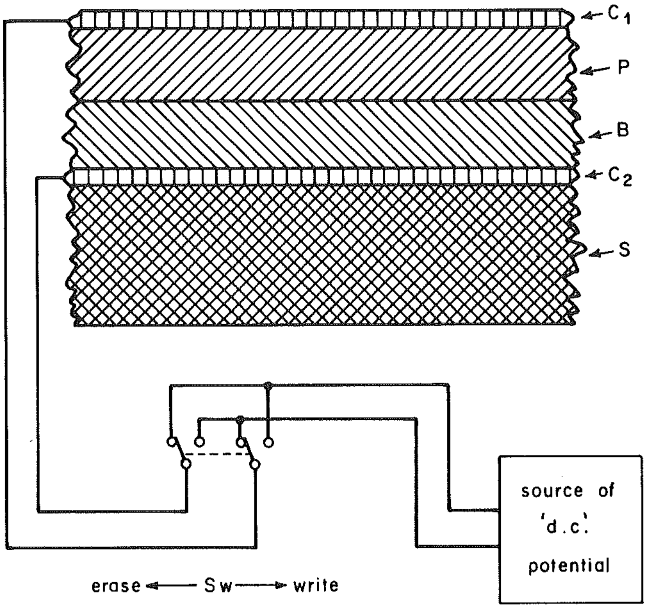

Fig. 16 - Ferroelectric photoconductive sandwich

C$_1$,C$_2$ — Ohmic conducting layers
B — Layer of bismuth titanate
P — Photoconductive layer
S — Substrate

Spatial frequencies of up to about 800 cycles/mm have been recorded, the required exposure being about an order of magnitude greater than required with 'holographic' photographic emulsions. The recorded information may be read as an amplitude hologram, in which case low diffraction efficiencies (of the order of 10^{-3}%) are obtained: higher diffraction efficiencies may be obtained by reading the recorded information as a phase hologram.[82] The spectral response of the material depends on the type of photoconductive material used: exposures at argon-laser wavelengths of 488·0 and 514·5 nm have been described.[81]

4.3.8. A thermomagnetic material

The ferromagnetic[83] material manganese bismuth has a Curie temperature of 360°C. If a thin film of the material is magnetised and local heating is then applied so that areas are raised above the Curie temperature, the remanent magnetism in these areas will be modified, and this modification will persist when the areas subsequently cool to below the Curie temperature. This effect has been used as a method of recording a holographic interference pattern[84,97] the local heating of the film occurring in the high intensity regions of the interference pattern. Heat is conducted away from these localised points on the film of material which should therefore have low thermal conductivity in order to obtain the required high resolution. For the same reason, the heating energy must be supplied as a pulse of very short duration. Mezrich[84] has used a 15 nsec pulse and an exposure of about 100 μJ/mm^2, (that is approximately 6 Kw/mm^2 during the pulse): in terms of total energy requirement the material is thus about 100 times less sensitive than photographic emulsions. Image reconstruction may be obtained either by transmission or reflection of the reconstructing beam from the hologram, using the Faraday or Kerr magneto-optic effects.[85] Diffraction efficiencies of about 0·05% have been obtained. The light forming the reconstructed image is polarised at right-angles to the light scattered from the reconstruction-beam (see footnote on p.6): by the use of a suitably-orientated analyser the effect of the scattered light can be considerably reduced.

Erasure of the recorded holographic pattern is obtained by re-magnetising the layer of material.

4.3.9. Photochromic materials

The optical transmission of some nearly-transparent materials decreases considerably when they are exposed to radiation.[98] In some organic substances this photochromic behaviour is produced by changes in the molecular structure,[86] while in some inorganic crystalline materials a similar effect is brought about by the redistribution of electric charges within the material.[73,87] This decrease of optical transmission is produced by radiation in the ultraviolet or blue spectral range, and the reverse 'bleaching' process occurs on exposure to radiation in the red and infrared spectral range. In addition, reversion to the nearly-transparent state occurs spontaneously: this makes the photochromic effect unsuitable for long-term holographic storage. Photochromic materials exhibit a relatively low actinic sensitivity (about 10^3 – 10^4 times less sensitive than photographic emulsions) and are likely to give low diffraction efficiencies as the holographic interference pattern is recorded as a change of optical transmission.

5. Recapitulation and conclusions

1. A hologram consists of a grating-like structure which is a replica of the interference pattern formed in the common volume occupied by two coherent beams of radiation. One of these beams emanates from an illuminated object, while the other (the 'reference' beam) has wavefronts of well-defined form (e.g. plane or spherical with known centre of curvature). A 'surface' hologram is two-dimensional and replicates a cross-section of the interference pattern, while a 'volume' hologram, as its name implies, it three-dimensional and replicates the interference pattern in depth. When a hologram is illuminated by a 'reconstructing' beam identical to the reference beam, the spatial amplitude and phase distribution of one component of the diffracted radiation is identical to that of the original radiation emanating from the object. A virtual image of the object is therefore formed, occupying the same position (relative to the hologram) as did the original object, and having an appearance (including its three-dimensional nature) identical to the original object. Other diffracted components of radiation may also be present, giving rise to spurious images.

2. If the object or the illuminating radiation is diffuse, radiation from any one point on the object will propagate through the complete volume in which the interference pattern is formed. Information about this object point will thus be distributed over the whole area (or volume if appropriate) of the resulting 'diffuse' hologram. During the image reconstruction process, a diffracted component of radiation corresponding to this original object point will therefore emerge from every part of the diffuse hologram: thus the presence of dust particles, blemishes on the hologram, etc., will not cause the entire loss of an item of information held by the hologram, as would be the case in a system (such as conventional photography) where such items are localised in specific areas of the recorded format.

3. Diffuse objects illuminated in coherent light appear to be overlaid by a random noise-like pattern (the 'speckle pattern') which is stationary if both object and observer are stationary. Speckle pattern also appears in the reconstructed image of such an object. This pattern is due to the interference of components of radiation scattered from different parts of the object.

4. Holograms can be formed on a number of light-sensitive materials, some of which offer advantages over the use of photographic film. These advantages include greater durability, re-usability of the material, immediate processing to 'fix' the recorded holographic pattern, and freedom from flare during image reconstruction caused by scattering in an inhomogeneous material. Photographic film, on the other hand, has the advantage of greater sensitivity compared with almost all presently available alternative media.

6. References

6.1. Author's note

Because the published material on holography is now very extensive, the references given in Section 6.2 should be regarded as introductions to the topics concerned. Reference 18 is recommended as a concise treatment of a wide range of holographic techniques. Reference 19 treats the subject in greater detail and from a more general mathematical point of view: it also includes reprints of References 1, 2 and 3. Both books contain extensive lists of references, as do most of the cited papers. The RCA Review of March 1972 (see References 93 – 99) gives a comprehensive treatment of holographic recording materials and also contains discussions of general holographic theory. Classified abstracts and lists of titles[20–27] have been prepared: recent papers are also listed in Sections 0·648 and 2·460 (08·27 before January 1973) of 'Current Papers in Physics' and in Section 2·970 (17·80 before January 1973) of 'Current Papers in Electrical and Electronics Engineering', both published by the Institution of Electrical Engineers.

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